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APPLICATION OF THE GEOPHONE TO MINING OPERATIONS

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ENGINEERING

BY

ALAN LEIGHTON

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CONTENTS.

	Page.
Preface	v
Acknowledgments	1
The detection of sounds coming through the earth	1
The geophone and its use	2
Principle of operation	2
Placing the instrument	3
Finding the direction	3
Horizontal plane	3
Vertical plane	5
In a mine heading	5
Details of the geophone	9
Results of experiments to determine the most satisfactory methods of using the geophone	11
Transmission of sound by rails	11
Transmission of sound along pipes	16
Interference in transmission of sound through coal and rock by "clay veins" and "faults"	17
Transmission of sound through the mine cover	18
Determination of direction	19
Geophone with nickel diaphragm	19
Use of geophone for rescue work	20
Procedure of the miner	20
Procedure of rescue party within the mine	22
Procedure of rescue party from the surface	23
Procedure of rescue party in metal mines	24
Use of geophone in mine surveying	24
Location of tunnel headings	24
Prevention of accidents in blasting through	25
Location of mine fires	25
Location of churn-drill holes	27
Location of the drift of diamond-drill holes	27
Location of "faults" and "clay veins"	28
Other uses of the geophone	29
Location of leaks in water pipes	29
Earth movements	31
Material for geophone diaphragms	31
Publications on mine rescue operations	32
Publications available for free distribution	32
Publications that may be obtained only through the superintendent of documents	33

TABLES.

Page.

TABLE 1. Distances blows can be heard with the nickel-diaphragm geophone ---- 19
2. Distance, under varying conditions, that mining machines can be detected by use of the geophone ---- 20
3. Sensitiveness of diaphragms of geophones made of different metals ---- 32

ILLUSTRATIONS.

Page.

PLATE I. Bureau of Mines geophone for use in mine rescues ---- 10
II. Leaky water pipe located by the geophone ---- 11
FIGURE 1. Cross section of geophone ---- 2
2. Manner of using geophones to obtain contact with the earth ---- 3
3. Geophones held against rock to note vibrations ---- 3
4. Method of locating the source of sound horizontally ---- 5
5. Method of locating the source of sound vertically ---- 5
6. Determination of source of sound at mine entry, sound being heard equally from both sides ---- 6
7. Determination in mine entry of source of sound, sound passing at left of observer ---- 7
8. Method of moving geophone to determine position of equal sound intensity ---- 7
9. Parts of the geophone for use in mine rescues ---- 10
10. Stretches across which sledge pounding can be heard with mica-diaphragm geophones ---- 13
11. Diagram showing location of pipe line in the experimental mine ---- 15
12. Location of the area of a mine fire by the geophone ---- 26
13. Vertical section of a metal mine in which a "clay" vein was located by geophones ---- 28
14. Diagram of intersection of two Pittsburgh streets, showing water-main leak located by geophones ---- 29

PREFACE.

Early in the World War, after the battle of the Marne, the battle lines had become stabilized and trench warfare and underground sapping or mining operations had been begun—first by the Germans, then in counterattack by the British and French—large mines were blasted under the trenches of the enemy, and smaller blasts, termed camouflets by the French, under his approaching headings. Both sides employed expert miners and the operations became more and more extensive; A. H. Brooks, formerly lieutenant colonel of Engineers, chief geologist of the American Expeditionary Forces, estimated in his book, "Military Mining," that at least 60,000 troops on either side were employed in mining operations. Blasts were so frequent in some parts of the battle lines that the morale of the troops was badly affected in sectors where the enemy had a greater number of skilled miners. Each side in turn attempted to get below the enemy's headings, until a depth of 150 feet is said to have been reached in the mining operations about Verdun.

Mining operations reached their height in the British operations at Messines Ridge on June 7, 1917, when a million pounds of high explosive was discharged in blasts covering a distance of 10 miles.

The first step of defense in military mining was naturally the employment of listeners to determine if an enemy gallery was approaching and to circumvent it by countermining. As an aid, various listening devices, devised by the French, were used for amplifying the sound of the mining operations—drilling, boring, and shoveling—transmitted through the ground.

The early listening instruments were adaptations of the telephone and the microphone. The French physicists developed the geophone and seismicrophone, which were used by the British and were studied and improved by American investigators of the War Department, and of the Bureau of Standards; later the geophone was improved further by the Bureau of Mines. A principle of the seismograph is used in the geophone, namely, a heavy suspended weight is attached to an elastic diaphragm or diaphragms, the inclosed frame being in contact with the ground as described in detail on page 2 of this paper.

The seismicrophone consists of a telephone transmitter having two carbon plates with carbon granules between that form a rela-

tively high electrical resistance which is varied by agitation of the granules. An electric circuit is set up, and as long as the microphone is undisturbed a steady current flows around the circuit and no noise is heard in the receivers. When a vibration of the earth occurs, the relative displacement of the diaphragm and the case changes the arrangement of the carbon granules, and consequently the resistance. There were many difficulties in the use of this instrument, however, as there was a tendency to confusion from extraneous noises, so that its field of usefulness was more limited than that of the geophone in spite of the obvious advantage of electric transmission of sound vibrations to a central station, avoiding thus the necessity of keeping so many listeners on duty. One of the great advantages of the geophone was the ability to survey accurately and determine by a method of triangulation based on simultaneous observation from a number of points with pairs of geophones, the location of the point where the noise originates. With a constantly produced earth vibration at a particular point, a high degree of accuracy in location is obtained by these surveys, both in the horizontal and the vertical plane. The device is not to be confused with air-vibration instruments for locating enemy artillery; it is actuated solely by means of sound waves transmitted through earth or rock.

From the capture of instruments in the shifting of the battle lines, information regarding listening devices became common to both sides. So efficient had become the use of these devices that by 1917 the war had practically developed into a drawn battle in underground operations, and after the great blasts at Messines Ridge military mining operations dwindled. It was not found profitable to employ a large number of troops in driving galleries, and therefore only listening posts were provided a little in advance of the front-line trenches. There was, however, another cause for the diminution of mining; namely, the increased use of artillery on both sides; the withdrawal of the bulk of forces from front trenches to the supporting trenches resulted, and a blast under front-line trenches became less important.

When the United States entered the war in April, 1917, mining was still considered important and the Corps of Engineers of the Army made preparations to carry on such operations. Accordingly, Maj. Gen. Black, Chief of Engineers, as part of the inquiry into military mining operations, requested the Bureau of Mines to make in the experimental mine near Pittsburgh, Pa., a study of the relative strength of sound waves through earth and rock given off by different kinds of mining machines and mining operations. This request led the chief mining engineer of the bureau, assisted by

W. L. Egy, physicist, and subsequently by Alan Leighton, to investigate the geophone and microphone. The specific object of the bureau's study was to determine how far enemy machines, such as boring machines, and sounds of hammering and of transportation might be heard, hence to plan counter operations and also to aid in the selection of mining machines that would make the least possible noise for the use of mining troops of the Corps of Engineers. These investigations were made under the supervision of J. W. Paul, chief of coal-mining investigation of the bureau.

This investigation continued until the end of the war, but as no military mining was undertaken by an American army the results were not applied. Had there been fortresses to besiege mining might have been resumed again. In the meantime Mr. Leighton, who had succeeded Mr. Egy as physicist of the bureau, had experimented with the geophone itself and had succeeded in increasing its sensitiveness.

The results disclosed the possibility of using the geophone in various nonmilitary ways. In mining, if men had been entombed by disaster, they might be located by their tapping, though the air unaided would not have transmitted the sounds. In detecting leaks in buried water mains, and in determining the limits of active fires in sealed areas, and in similar objectives the geophone would be of great value. The Bureau of Mines accordingly equipped its mine rescue cars with geophones to be in readiness at a disaster for the rescue of entombed men and for miscellaneous purposes.

One of the future possibilities of the subject appears to be the development of recording geophones to give records in deep mining of ground readjustments or movements which probably precede disastrous caving, wind blasts, or "bumps," as they are termed in coal mining.

GEO. S. RICE,
Chief Mining Engineer.

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THE GEOPHONE AND ITS USES.

By ALAN LEIGHTON.

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THE DETECTION OF SOUNDS COMING THROUGH THE EARTH.

Sounds coming through the earth and heard in the air are generally very faint. Sometimes, however, earth sounds can be heard by placing the ear next to the ground, as vibrations of the earth are transmitted, by contact, to the little air space between the surface of the soil and the eardrum. The detection of sound may be improved by burying any large receptacle in the ground, filling it with water, and holding one's ear far enough in the water of this vessel to cover part of the face and head. Instead of placing the head in water, the observer may use a receptacle similar to a soldier's canteen, placing it on the ground and filling it with water, except that a small air space is left in the upper part of the neck. By fitting to the small neck of the canteen a rubber tube terminating in a suitable metal tip placed in the ear, earth sounds can be heard. The little air space imprisoned in the upper part of the canteen will serve the same purpose as the air confined in the ear in the previous experiments. The results obtained are generally slight, except with the canteen, but they can be improved greatly by the use of stethoscopes or similar instruments. The geophone is such an instrument.

THE GEOPHONE AND ITS USE.

The mine geophone is sensitive and reliable, yet extremely simple and easily portable. The instrument was invented by the French during the war to detect sapping and underground mining operations. It was developed by the United States Engineers, and the instruments now used by the Bureau of Mines were made according to plans drawn by them, except for the introduction of different diaphragms. The instrument consists of a cast-iron ring about $3\frac{1}{2}$ inches in diameter, as shown in figure 1, in the center of which is suspended a lead weight fastened by a single bolt through two metal disks or diaphragms; one of the disks covers the top and the other the bottom of the iron ring. There are two brass cap pieces, the top one having an opening in its center to which is fastened a rubber tube leading to a

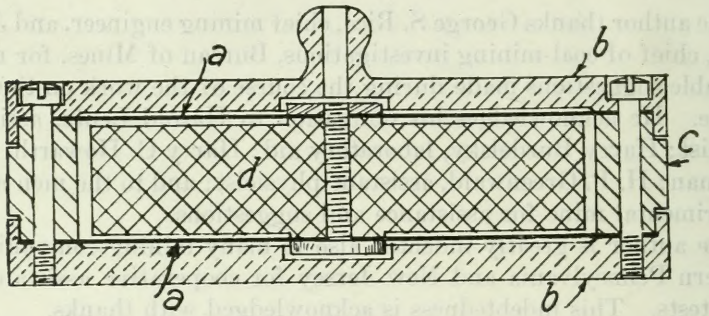


FIGURE 1.—Cross section of geophone: *a*, metal or mica disk; *b*, cap plate; *c*, iron ring; *d*, lead weight.

stethoscopic earpiece. These cap pieces are fastened with bolts to the iron ring, are slightly recessed, and serve to hold the diaphragms in place. The extreme sensitiveness of the instrument is obtained by having the right proportions between the size of the lead weight, the size and shape of the case, and the thickness and quality of the diaphragms.

PRINCIPLE OF OPERATION.

The geophone is essentially a small seismograph, as it embodies the same principles as the ponderous apparatus that records earthquake tremors. It really consists of a lead weight suspended between two elastic diaphragms cutting across a small air-tight box. If the instrument is placed on the ground and anyone is pounding or digging in the vicinity, energy is transmitted as wave motion to the earth, and the earth waves shake the geophone case. The lead weight, on account of its mass, and because it is suspended between the disks, remains comparatively motionless. Thus a relative motion is produced between the instrument case and the lead weight, with the result that the air in the instrument case is com-

pressed and rarefied. As the rubber tube leading to the stethoscopic earpiece is connected with the air space in the geophone, this rarefication and compression of the air is carried to the eardrum. Usually two instruments are used, one for each ear. The geophone, therefore, transforms the earth wave into an air wave, which is heard by the ear as sound, and at the same time magnifies the wave so that the sound is louder than if the ears were placed in direct contact with the earth.

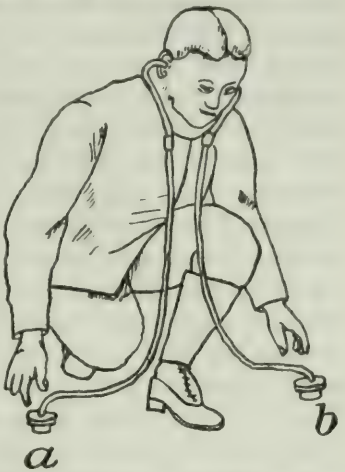


FIGURE 2.—Manner of using geophones to obtain contact with the earth: *a* and *b*, geophones with rubber tubes connected to stethoscopic earpieces.

PLACING THE INSTRUMENT.

In order to hear sounds through the earth the instrument must rest on natural ground. The soil should be carefully cleared and smoothed, and the instruments should be pressed firmly into place in order that the contact between them and the earth may be intimate. (See fig. 2.) For listening through coal or rock they may be placed on any solid natural shelf, or for coal on a niche made in the face or rib. To hold the instruments against the coal rib or face with the hands is not satisfactory, because the circulation of the blood in the hands causes vibrations that are distinctly audible through the instrument. Rock is apparently firm enough to prevent interfering vibrations, and very satisfactory results can be obtained, therefore, when the instruments are held against it. (See fig. 3.)

FIGURE 3.—Geophones held with the hands against rock to note vibrations traveling through the rock.

FINDING THE DIRECTION.

HORIZONTAL PLANE.

It is an established physiological fact that men instinctively estimate the direction from which a sound is coming through the air.

When the sound is coming from the right, one hears it entirely with the right ear, and similarly on the left; but as the head is turned there is a point, which the ear is able to judge exactly, where the sound is heard equally in both ears and is therefore judged to be coming from in front or from the rear. This matter is largely one of equality of phase, or the time of arrival at each ear of corresponding sound-wave phases, and not a question of intensity. Thus a man with considerable difference in the sensitivity of his ears may still determine direction. When one is already facing in the general direction from which a sound is coming, the most accurate method of locating direction is to turn the head to the right, for instance, until the sound becomes perceptible only to the left ear, then to the left until the same sound becomes perceptible only to the right ear. By turning the head alternately to right and left, the sound is made to pass successively from right to left and from left to right. By decreasing progressively the range of these oscillations of the head, one will stop in a position exactly in line of the sound. As will be seen later, the sensation of the passage of sound from one ear to the other is very important.

Similarly, by the use of two geophones, one instrument to each ear, it is possible to determine the direction from which a sound is coming through the earth. Two geophones are placed on the ground with an interval of 2 to 3 feet between them, and if they are connected to suitable earpieces terminating in each ear, with pieces of rubber tubing of equal length, the arrangement is equivalent to placing both ears on the ground at the same time. As soon as a sound is heard, the observer notes whether the sound comes from the right or from the left. He then shifts the geophones with his hands, and succeeds by a series of tentative changes in their relative positions in finding a place for them where the sound seems to come from the front or rear and not from the right or left. A perpendicular erected halfway between the instruments will therefore give the direction of the source of sound, or, more accurately, the projection of this line of direction on the horizontal plane will pass through the source of sound.

Another line of direction of the propagation of the sound may be obtained by repeating the operation just described in another place—whether or not situated on the same level as the first point. These two lines of direction are projected on a plane, their intersection giving at once the source of sound. This procedure, as is apparent, gives no indication of the elevation of the source of sound with relation to the observer. If it is desired to discover the vertical level of this point, it is only necessary to make an additional test analogous to the two preceding tests, this time on a vertical surface.

VERTICAL PLANE.

To illustrate: Let the plane KLDC (see fig. 4) be a horizontal plane. A sound originating at point O without the plane is observed with the geophones from a point A, and its direction determined as AG. Similar observations at B show its direction from that point as BH. The intersection of these lines at O, of course, gives the horizontal location of the sound source; and although it shows nothing in regard to the elevation of the sound source, it at least shows that the sound source is within a vertical line at O, which in turn is within EO erected perpendicular to line DC.

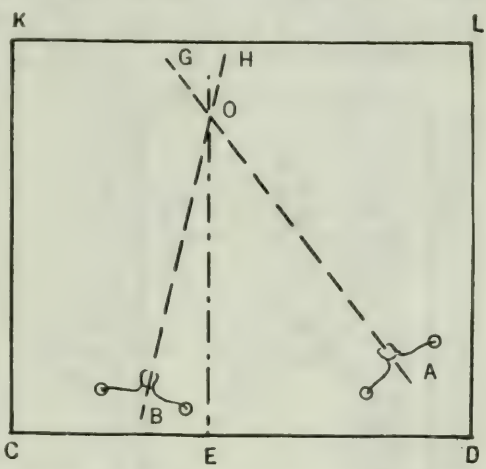


FIGURE 4.—Method of locating the source of sound horizontally.

Now, in figure 5, let plane KLCD be a vertical plane whose base is the line CD of figure 4. The observations have shown that the sound source is within a plane EM erected perpendicular to DC at E. Observations of the sound are now made on plane KLCD with the geophones at point N. These instruments show that the sound source is within a plane NP, also perpendicular to the plane KLCD. Evidently the intersection of this plane with the plane EM along the line O shows the elevation of the sound source above the plane DC, or EO is the desired elevation.

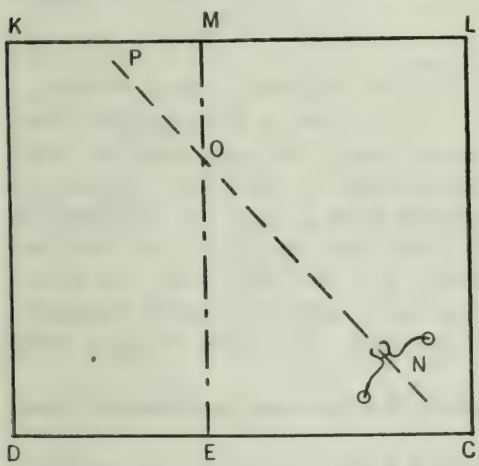


FIGURE 5.—Method of locating the source of sound vertically.

IN A MINE HEADING.

Suppose, then, that a determination is to be made at the head of a mine entry r_1r_2 (see fig. 6). The geophones s_1 and s_2 are placed on the ground at a and b. The observer is not represented, but the double earpiece e represents his position.

With the instruments in the position *ab*, if the observer hears sounds on the right, through s_2, he may, to face these sounds, either revolve the position of both instruments, or, more conveniently, move one only, the other remaining stationary. In the present example the geophone s_2 must be moved far enough from the direction of the source of sound, which is on the right, for the sound to pass definitely to the left, in order to determine at once the position facing the sound. The instrument s_2, therefore, should be moved from *b* to *b'*.

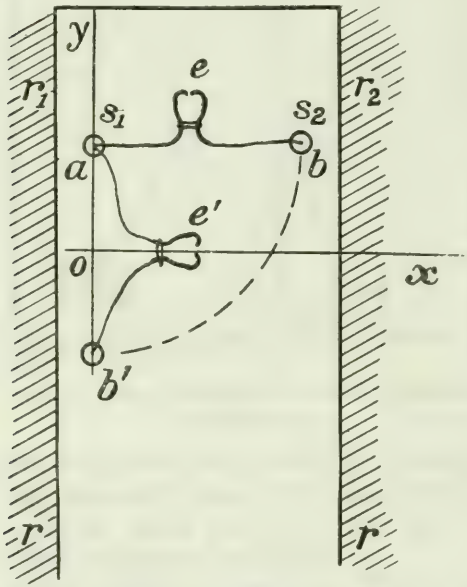


FIGURE 6.—Determination of source of sound at mine entry, geophone being moved far enough for sound to be heard equally from both sides.

Thus the observer is confronted with two possible situations: Either the removal from *b* to *b'* is enough for the sound to be heard on the left, or it is not enough, and the observer still hears on the right. In the first place the correct position of s_2, or that which will make the sound heard equally in both ears, is included between *b* and *b'* on the arc of the circle described. The point of impact is situated in the angle *xoy*.

In the second case, to make the sound pass to the left, s_2 must be drawn farther back, or, what amounts to the same thing, the geophone s_1 must be advanced from *a*. The instrument s_2 will then be left in place at *b'*, and s_1 will be moved from *a* to *a'* as indicated in figure 7. The observer will then have his back to the end of the mine entry, and obviously will this time hear the sound on his left. The correct position for s_1 will be included between *a* and *a'* on the arc of the circle described. The point of impact will be situated in the angle *xoy'*.

To complete the determination in the first case, as shown in figure 6, the method is as follows:

As in the position *ab* the sound is heard on the right, whereas in the position *ab'* it is heard on the left, the instrument s_2 should be moved to and fro in such a way that the sound will pass from one ear to the other with a constant reduction of the range of the

displacements. Consequently, the instrument s_2 is placed successively in the positions marked 1, 2, 3, 4 (see fig. 8), selected so that the sounds are heard alternately on the right and on the left, on the right in positions 1, 3, and 5, and on the left in positions 2, 4, and 6. These positions are immediately marked on the floor of the mine, as shown in the lines of figure 8. Thus two groups of lines are developed, confining the correct position more and more closely. In this series of tests the instant finally comes when the distinction between the sensation on the right and that on the left becomes imperceptible as the desired position is approached, as, for instance, when the position 7 is tested after positions 5 and 6. Hence it is advisable to ignore the doubtful position 7, and to register only the positions where the distinction of the sound as coming from right or left is clearly defined. For this reason the line marked 7 should be obliterated. The instrument s_2 should be replaced in position 5—the last one where the position of the sound is still clearly discernible as on the right—and then should be moved to position 8 to see whether the sound passes clearly from one ear to the other. If the positions 5 and 8 are very near together, one may assume, without committing a serious error, that the position sought is halfway between the marks 5 and 8. In actual practice the positions 5 and 8 will often be so close that they almost

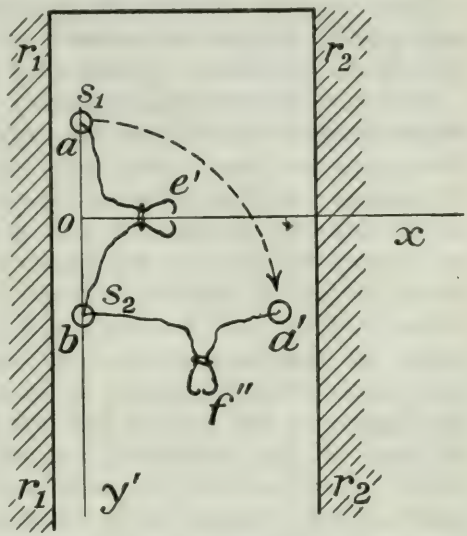


FIGURE 7.—Determination in mine entry of source of sound, geophone being moved far enough for sound to pass to the left of the observer.

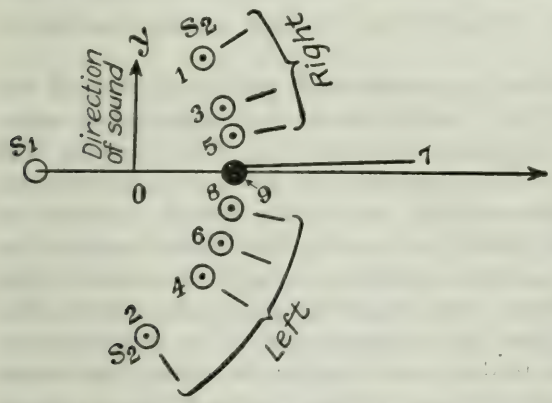


FIGURE 8.—Method of moving geophone to determine position of equal sound intensity in finding direction.

coincide. After the desired position has been found, it yet remains to erect the perpendicular oy at the point o on a line connecting the center points of the two geophones.

If the operator is skillful the complete determination can be made very quickly without the necessity of marking the successive positions of the instrument s_2 on the mine floor.

As a further check, the geophone s_2 may be placed at the point 9, where the sound should be of the same intensity in both s_1 and s_2 if these points have been well chosen. If the points are not well chosen, the listener will often be able to improve and correct their position by striking with his finger at o, at an equal distance from s_1 and s_2, and timing the blows of his fingers with the blows of the tool to which he may be listening. Directly after each blow is heard the listener will tap with his finger at o with an intensity calculated to render the same impression on his ears as does the blow from the tool that he is trying to locate. If the instruments are suitably placed the finger taps will seem to have the same origin as the strokes of the tool. If the instruments are not suitably placed, the strokes of the tool will at once seem to be on the right or on the left of the center, and the listener will be left to correct the position of the two instruments. He may find on the straight line s_1s_2, to the right or left of point o, some point where the finger strokes seem to be delivered in the same position as the blows of the tool. If this point is somewhat to the right of o, s_2 must be moved back a little; if the point is somewhat to the left of o, s_2 must be moved forward; and so on until by striking at the middle of the line s_1s_2 a sensation similar to that of the blow from the tool or other mining machine is produced.

By operating methodically, as indicated, and by tracing all the positions "right" and "left" on the ground, it is impossible to make an error in the determination of the direction. The observer will always face the sound. Yet experience has shown that listeners do not always proceed systematically, but, having found a position in which the sound is "in front," they really have their backs to the source. To avoid such a serious mistake, it is often desirable for the listener, after he has chosen what he considers to be the correct positions for s_1 and s_2, to place his instruments on a line perpendicular to the line s_1s_2, in order to determine whether the sound then comes from the right or from the left, and whether he was facing the source of the sound or had his back toward it in his chosen position.

After the foregoing discussion of the general manipulation of the geophone for sound perception and for finding direction, it is necessary, for a complete understanding of the instrument and its uses, to give a detailed description of its construction, and to direct atten-

tion to a few precautions that must be taken if accurate determinations are to be made.

DETAILS OF THE GEOPHONE.

A complete set of mine rescue geophones, as used by the Bureau of Mines, consists of two geophones, with rubber tubing for connecting the instruments to an ordinary stethescopic twin earpiece.

The parts of each geophone and the assembly are shown in detail in figure 9 and in Plate I. They consist of—

1 brass top plate.
1 brass bottom plate.
1 cast-iron ring.
2 metal diaphragms.
1 lead weight.
1 screw with nut for fastening weight to diaphragm.
6 screws for bolting parts together.
2 rubber tubes, ¼-inch diameter, heavy walled.
1 stethescopic twin earpiece.

As before stated, the sensitiveness of the instrument is obtained by getting exactly the right proportion between the size of the lead weight, the size and shape of the case, and the thickness and elasticity of the diaphragms.

The brass plates and the cast-iron ring should be made exactly to plan, unless it is more desirable to fasten them together with six No. 8–36 screws than with six No. 8–32 screws, as specified.

The lead weight, if desired, may be made in three parts, consisting of a flat disk ½ inch thick, and two lead washers $\frac{1}{32}$ inch thick, upon which the metal disks are to be seated. It is more satisfactory, however, to make the weight from a solid piece.

The diaphragms should be made from pure nickel sheet 25/1000 inch thick, or rolled Non Gran bearing-metal 30/1000 inch thick. The material must be uniform in thickness.

The rubber tubes should be of exactly equal length, from 2 to 3 feet, of ¼-inch internal diameter heavy walled tubing. If one tube is shorter than the other the sound will apparently be louder through the shorter tube. The reason for this is evident, as the ear distinguishes the difference in the time that sounds are produced in each instrument, and any difference in the length of the tubes would cause apparent variations in time. The 2-foot tubes have been found very convenient in mine work, but the longer tubes save stooping. It is essential that the tubes be heavy walled, so that they will not kink or twist easily. The tubes should always be kept fastened to the geophones and to the earpieces, otherwise particles of dust and dirt may find access to the top chamber of the geophone, greatly interfering with successful operation.

The stethescopic earpieces must fit so closely into the ears as to close the ear passages completely. For this purpose they must have

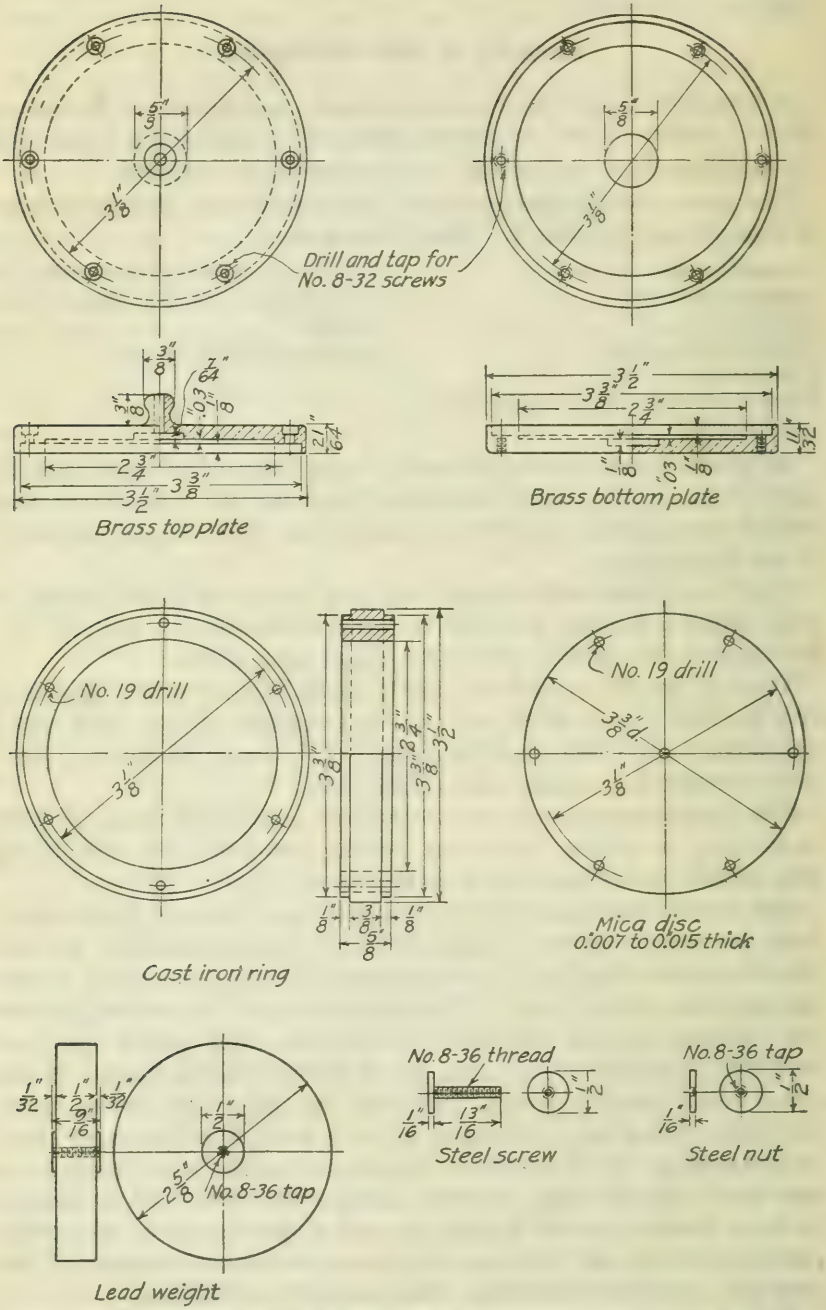
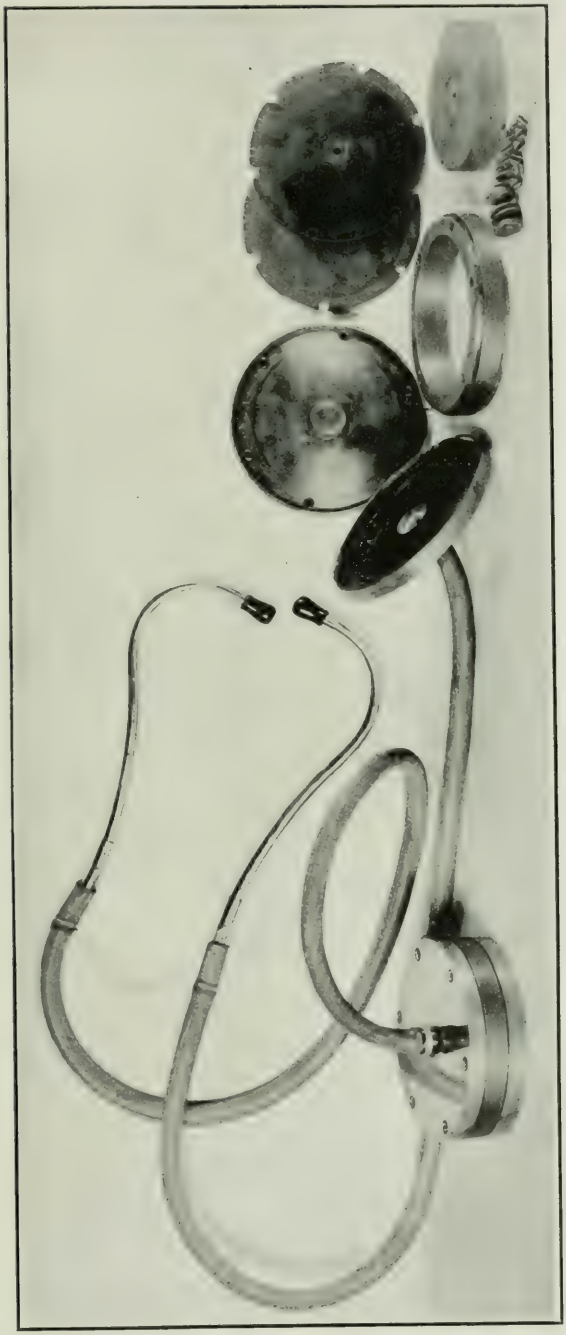
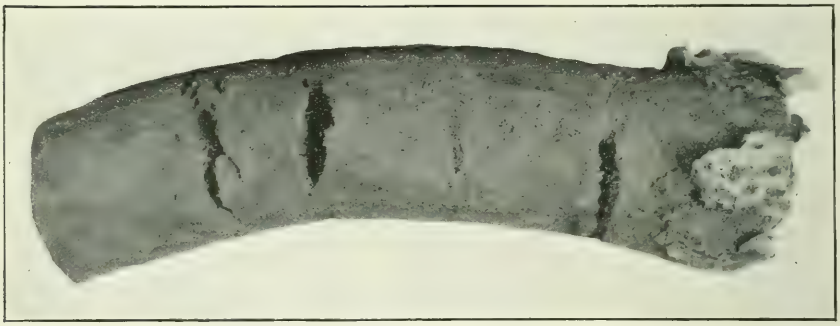


FIGURE 9.—Parts of the geophone for use in mine rescues by the Bureau of Mines.



BUREAU OF MINES GEOPHONE FOR USE IN MINE RESCUE WORK.



LEAKY WATER PIPE LOCATED BY MEANS OF THE GEOPHONE.

a stiff spring. If the spring is not strong enough it may be supplemented with a rubber band looped over the tubes. The ordinary stethescopic earpieces are provided with tips that point slightly forward when the earpiece is adjusted in the ear. This arrangement allows them to follow closely the direction of the ear passage, and prevents any trouble in hearing that would be caused if the open ends of the tubes should press anywhere against the ear wall, cutting off the sound. Rather small tips are desirable. The usual tip is made of wood, and is satisfactory; but if a soft rubber tip is obtainable it is much better, for it rests more comfortably in the ear.

RESULTS OF EXPERIMENTS TO DETERMINE THE MOST SATISFACTORY METHODS OF USING THE GEOPHONE.

The results of experiments undertaken to determine the conditions of operation under which geophones give the most satisfactory results in rescue and in mine survey work are summarized in the following pages.

For use in determining the best ways of operating the geophone for rescue work and for surveying, the data must show two things: (1) The proper place to locate the geophone, and (2) the proper place to pound when it is desired to detect sounds and to determine their point of origin.

In the experiments described it was necessary to determine whether blows from different mining tools could be heard farthest when struck on the floor, on the roof, or on the rib; also whether the geophones would operate more satisfactorily when the instruments were placed on the floor or on the rib. It was likewise desirable to ascertain the effects of intervening rooms, entries, faults, and clay veins on the transmission of sound. Under certain conditions sounds are transmitted well along pipe lines and rails, therefore it was necessary to find out also how these distances compare with the distances that sounds could be detected through the coal or rock. Finally, it was essential to determine just what could be expected from the geophones when they were used upon the surface for the detection of sounds coming from a mine below.

The pounding for the greater part of this work was done with a 16-pound sledge; but comparison was made between the distances that blows from the sledge, and blows from a pick, tamping bar, stick of timber, shovel, and a 10-pound rock could be heard. These comparisons of distance show in general that the sledge can be heard at a greater distance than any other tool. Pounding with a heavy rock was heard nearly as far as that with the sledge, whereas pounding with a pick, a bar, or a stick of timber under similar conditions was heard about three-quarters as far. *Blows with a sledge can be de-*

tected farther with the geophone than the blows from any other hand-operated mining tool. In coal mines, the blows should be struck on the coal rib or face.

The above conclusions were reached after many experiments had been conducted in the coal mines about Pittsburgh. Of these tests those made at the experimental mine were perhaps the most complete, and for that reason they are described here. Attention is called to the fact that at the time these experiments were conducted mica diaphragms were used in the geophones. In addition, the coal at the experimental mine does not transmit sound as well as does the coal at the neighboring mines. Consequently any figures given in connection with these experiments are of comparative value only. At the end of this chapter is a table showing the distances that sounds of different character should be detected by means of the geophone.

Preliminary measurements showed that the sound was transmitted equally well in any horizontal direction through the coal strata. It was also found that pounding on the coal face or rib was heard nearly as well across rooms and entries as through solid coal at the experimental mine. Later work carried on in a neighboring mine seemed to show that the total distance a sound could be detected through the coal was diminished about 12 feet by each intervening room. When mica diaphragms were used in the geophone at the experimental mine, sledge pounding was heard from 600 to 650 feet across four entries and five rooms, across two entries and one room, diagonally across No. 1 butt and five rooms, and across the air course, entry, and right butt. These directions are indicated on the attached map of the experimental mine in figure 10. A careful investigation has been made of the comparative distances, from the right butt out the entry, that various tools can be heard when pounding is done on the rail, on the floor, on both coal ribs, and on the roof; also when the geophones are located on the floor, on both rails, on the loose earth between the rails, and in a niche in the coal rib. These observations are tabulated in Table 1, and show conclusively that the sound is best transmitted, and can be detected farthest, when the pounding is on the coal rib and when the receiving instruments are also located on the rib, although if the floor is clean and solid, the sound is received about as well with the geophones on the floor close to the rib. This fact is important in considering the problem of determining the direction of the sound.

In connection with determining the distance that sounds from different mining tools can be detected, a study was made of the characteristics of sounds from mining machines as they are reproduced by the geophones.

Twelve mining and carpentering operations were carried out on the coal about 200 feet away from a mining engineer equipped with

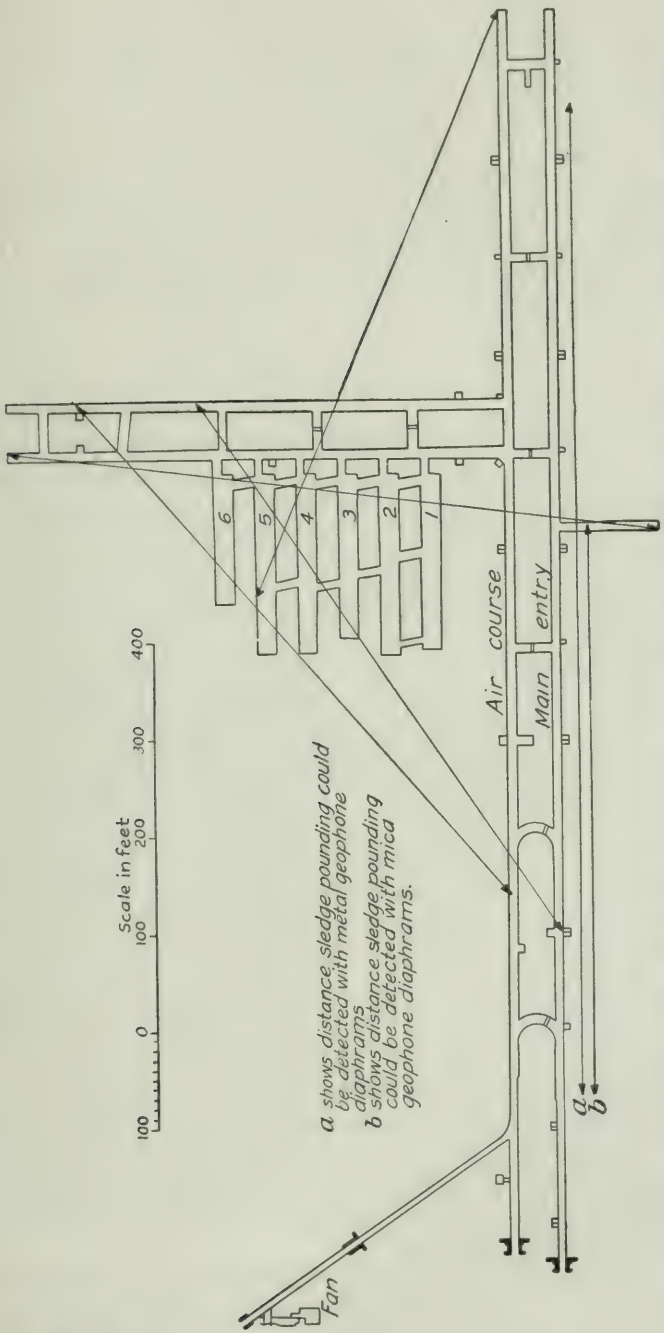


FIGURE 10.—Stretches across which sledge pounding can be heard at the experimental mine with mica-diaphragm geophones.

the geophones. This engineer had had no previous experience with the instruments and did not know what tools were to be used except that they would be mining or carpentering tools. The engineer was able to name correctly 9 of the 12 tools and was able to give an accurate description of the sounds from the other 3. This series of tests shows how well sounds are reproduced by the geophone.

Later experiments conducted with geophones having nickel diaphragms showed that at the experimental mine ordinary talking and singing could be detected through 150 feet of solid coal, and that these sounds were very loud through a 50-foot coal pillar. The pitch of the sounds was well reproduced. The transmission of sound was poor, however, so that talking was understood only with difficulty.

TRANSMISSION OF SOUND BY RAILS.

Rails and pipe lines can not be relied upon to transmit the sounds from blows of different sorts unless these lines are properly suspended throughout their length. Among the tests leading to this conclusion the following may be cited: The track in the experimental mine is laid with 20-pound rails connected with fishplates. It was found that pounding with a heavy sledge on these rails could not be heard over 400 feet. As the sound could be heard equally well on either rail when the pounding was on one rail only, it seemed that the sound must pass from the rail to the floor and back again into the rail. This opinion seemed to be confirmed when pounding on the rail up to No. 1 butt (see fig. 11), about 400 feet from the entry, could just be detected if the geophones were placed on the rail in the entry, although there was no connection of consequence between these rails. Also, a trip of cars between the pounding and the observer made no difference in the transmission. The track in the mine is buried in coal and shale dust, and, as is shown later, the earth prevents sound transmission along pipes or rails.

For further study, the work was transferred to the incline near the tipple, where the track is laid with 30-pound rails. It was found that the sound of the sledge was transmitted about 425 feet, whereas the pick could be heard 250 to 300 feet. Measurements were made on a stretch of unbroken track and also on a track that included one switch. The distances were the same in both tests, and again the sound of pounding on one rail was transmitted equally well on both rails. As the sledge can be detected about 400 feet through frozen clay, it is reasonable to suppose that the sound is transmitted through the earth rather than through the rails.

Another series of experiments was performed on the Baltimore & Ohio Railroad track between the experimental mine and the station at Wallace. This track is laid with about 80-pound rail connected

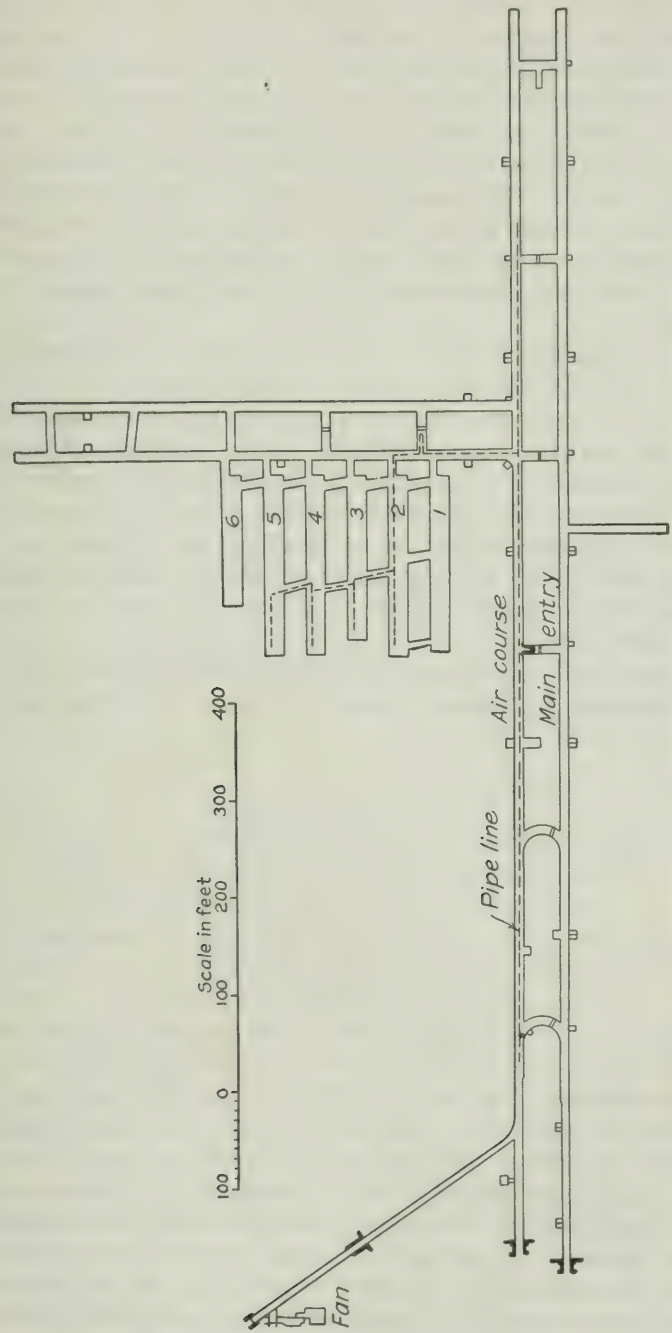


FIGURE 11.—Diagram showing location of part of pipe line in the experimental mine.

with angle bars. On the first day the temperature was below freezing and the roadbed was frozen. The sledge could be detected 1,350 feet, and the sound was transmitted, as before, equally well on both rails. Later experiments—after the weather had moderated enough to melt the ice along the roadbed and to expand the rails—showed that the sledge could be heard about 2,000 feet with the geophones and 1,500 feet by placing the ear against the rail. Here the transmission was not the same on both rails, being about three-quarters as far on the off rail. On a sidetrack running into the main line the pounding was not heard over 900 feet. As this track is well buried in sand, however, the damping effect rather than the switch may explain the difference.

Owing to the fact that the sound is seemingly transmitted through the floor of the mine rather than directly through the rails, it was impossible to study the effect of switches, frogs, various bonds and joints, the size of rail, and curves, as well as of falls and barricades. The experimental work on pipes shows clearly that loose sand damps sound vibration and, conceivably, a fall or barricade might cut off entirely the transmission of sound energy through the rails.

It has been found that the rails have the property of picking up and intensifying any air sound. This fact also seems to be true of cross shelves in the mine.

If blows can be struck on the end of a rail, the distance the sound can be detected is increased about one-half. The vibration is still damped by loose earth.

TRANSMISSION OF SOUND ALONG PIPES.

Most of the pipe lines in the experimental mine run either in the coal rib or along the side of the track buried in the shale dust of the floor. One compressed-air line, however, runs from No. 1 butt into No. 2 room, and after entering the room continues diagonally across the cut-throughs to No. 5 room, a distance of about 350 feet. (See fig. 11.) Throughout its course through the rooms the pipe is laid on ties, thus being completely exposed. The geophones were placed at the end of the pipe in No. 5 room, and pounding with an 8-inch hammer was done at the mouth of No. 2 room. The sound was transmitted so well that it was audible to anyone standing within 25 or 30 feet of the pipe in No. 5 room. The pipe was buried at a point about 15 feet down the butt from the neck of No. 2 room, and it was found that pounding with a heavy sledge at this point could not be detected through the pipe in No. 5 room, though the sound did come through the mine floor. In other words, the 15 feet of covering completely prevented the transmission of sound energy along the pipe. A number of observations were made regarding the distance

that pounding with various tools could be detected on pipes in the air course, but all results tended to show that the sound was coming through the earth as well as through the pipes. If a pipe line is suspended, it appears that the sound will be carried a long distance; in fact, light hammering with the knuckles has been detected 1,500 feet along a 6-inch pipe laid on ties down an inclined shaft.

In connection with the transmission of sound along pipe lines, other facts are of interest. At a mine in the vicinity of Pittsburgh there is a discarded 6-inch pipe line about 300 feet in length running from the surface to the mine below. It is possible to use this line as a speaking tube, yet sledge pounding upon one end of the pipe could not be detected with geophones placed at the other end, although, of course, this pounding could be heard faintly when the ear was pressed against an opening in the pipe. In another district the throbbing of a pump could be heard when the geophones where placed upon the ground about 3 feet above a gas main. It was ascertained that the pump was at least a mile and a half away. Furthermore, as is described later, when tests were made to locate a leak in a water pipe, the sounds from the leak were transmitted for a considerable distance through a buried pipe. These observations all lead to the same conclusion: Although vibrations transmitted to pipe and rails are quickly damped by loose earth, if the vibrations can be set up in the contents of the pipe—water, gas, or air—these vibrations are transmitted great distances. To test this conclusion a small diaphragm was placed on the end of the compressed-air line at the experimental mine. Where a blow upon the pipe could have been heard through but 15 or 20 feet of buried pipe, the sound of the blow upon the diaphragm could be detected at least 900 feet away. The transmission of sound ceased as soon as a valve between the pounding and the observer was closed.

INTERFERENCE IN TRANSMISSION OF SOUND THROUGH COAL AND ROCK BY CLAY VEINS AND FAULTS.

As would be supposed, sound is not transmitted as well through clay veins or "faults" as through denser material. It has also been found that these veins or faults interfere greatly with attempts to determine the direction from which sound is coming. At 650 feet in the experimental mine, sledge pounding across one vein about 10 feet wide was located consistently by two people as being 15 to 20 degrees to the left of the true direction. At 45 feet, through a coal pillar which this vein cut diagonally, it was practically impossible to ascertain the true direction more closely than 30 to 40 degrees. That the transmission of sound may be cut off almost completely by "clay veins" is shown by the result of encountering a clay vein in a metal mine; sledge pounding could not be detected 150 feet away.

TRANSMISSION OF SOUND THROUGH THE MINE COVER.

Observations made over the experimental mine through the greatest depth of cover—138 feet—show that pounding on the rib with either a timber or a sledge can be perceived on the surface anywhere within a circle whose diameter is 700 to 800 feet, the pounding, of course, being located at the center of this circle. Pounding on the roof with the timber makes a deeper and more easily detected sound, but it can not be heard as far by 50 feet or so as pounding on the rib.

Before the close of the World War the allied armies had developed a device for fastening the geophones to the end of a long, jointed wooden rod, which was run through a pipe driven toward the German trenches, and which making contact with the earth at the far end of the pipe, transmitted sounds to the geophone that would not come so far through the clay. It seemed that in the observations made above a mine, in case the ground were very soft, there might be some advantage in driving stakes through the earth to firmer ground, and in placing the geophones on the stakes. If a person were covering the ground above a mine where miners were entombed, he probably could not well spend time to drive stakes more than 2 or 3 feet. Therefore the stakes used in these experiments were not very long.

The spot selected above the experimental mine was at the point where the cover is thickest, 138 feet, and where the ground had been found to be the softest. Six stakes were driven into the ground: (1) A pine stake 2 by 4 inches and about 3½ feet long, driven in about 2½ feet; (2) a pine stake 2 by 4 inches and 1½ feet long, driven completely in; (3) a 2-inch iron pipe 3 feet long, driven completely in; (4) a ¾-inch pipe 1½ feet long, driven completely in; (5) a 1-inch solid pipe 1⅓ feet long, driven completely in; (6) a flat iron bar about ¾-inch by 2 inches and 1½ feet long, driven completely in. Blows were struck with a sledge in the mine just strong enough to be heard faintly but clearly when the geophones were on clay with the sod removed. Whenever the geophones were placed directly on the earth, the sounds were immediately detected; but with the instruments on top of any of the stakes, the sound was detected with difficulty, though it was heard in every case. The sound was heard best with the geophones on the clay, next best on the wooden stakes, next on the solid iron rod, and least clearly on the iron pipes. Therefore it appears that under ordinary conditions such stakes are of no value.

The distance that sounds can be detected through the mine cover will vary greatly, of course, with the nature of the strata and the weather conditions, as even a slight wind interferes greatly with the

observations. Sledge pounding within a mine has been detected through 550 feet of cover when a geophone having nickel diaphragms was used.

DETERMINATION OF DIRECTION.

Observations on rails and pipes showed that here the direction from which the sound was coming was easily determined. The accuracy of determinations of direction when made in the usual manner within the mine vary considerably with the nature of the material on which the instruments are resting, as well as with the experience of the observer. It is well to move the instruments about freely in order to overcome any errors due to faulty transmission of sound through limited sections of the rock or coal. Although the accuracy of sound determination varies in different mines, later observations with geophones equipped with metal diaphragms have shown that by averaging results from a number of determinations very accurate measurements can be made. If the rock, coal, or earth is homogeneoeus, and the geophones are resting firmly upon the ground, the following degrees of accuracy may usually be expected.

Degree of audibility.

	Degrees.
Maximum distance of audibility	4
Three-fourths distance of audibility	3
One-half distance of audibility	2

Very little trouble has been experienced in finding direction on the clay outside the mine.

All of the foregoing observations have been checked by observations made in various mines. The one conclusion to be drawn is that in a metal or coal mine, for purposes of sound detection, blows should generally be struck on the rock or on the coal. Similarly, the geophones should be located on the rock or on the coal.

GEOPHONE WITH NICKEL DIAPHRAGM.

With the nickel-diaphragm geophone it should be possible to hear the different mining operations for the following distances through rock, coal, clay, and the mine cover:

TABLE 1.—*Distances blows can be heard with the nickel-diaphragm geophone.*

	Through rock.	Through coal.	Through clay.	Through mine cover.
	Feet.	*Feet.*	*Feet.*	*Feet.*
Sledge	3,000	2,000	400	550
Pick	2,400	1,600	320	440
Timber	2,250	1,500	300	400
Copper-tipped tamping bar	2,400	1,600	320	440
Ten-pound rock	2,625	1,750	350	480
Shovel	2,250	1,500	300	400

TABLE 2.—*Distance under varying conditions that mining machines can be detected by use of the geophone.*

Machine.	Operation location.	West rail.	Geophones on—			
			Other rail.	Floor between rails.	Niche in rib.	Floor.
		Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Sledge	West rail	275	275	275	475	275
	Floor	375	375	375	525	375
	Near rib	525	525	525	600	525
	Far rib	525	525	525	600	525
Pick	West rail	350	350	350	375	350
	Floor					
	Near rib	375	375	375	475	425
	Far rib	375	375	375	475	425
Timber, 4 feet by 3 by 5 inches	West rail	300	300	300	425	300
	Floor					
	Near rib	300	300	300	300	300
	Far rib	300	300	300	450	300
	Roof	375	375	375	450	350
Copper-tipped tamping bar	Near rib				475	
	Far rib				475	
10-pound rock	West rail	325			425	
	Near rib				525	
	Far rib				525	
Shovel	Near rib				425	
	Far rib				425	

USE OF GEOPHONE FOR RESCUE WORK.

Experimental work has shown that if the geophone is to be used in a coal mine to detect sounds coming through the strata, the instrument should be placed on a niche or shelf of coal rather than on the floor of the mine. Similarly the experiments conducted by the bureau have shown that if a blow is to be struck in a mine with the purpose of being detected by the use of the geophone, the blow should be struck upon the coal.

The foregoing principles are fundamental ones that underlie all the suggestions made (1) for the underground procedure of a miner entombed in a coal mine who expects to be located by a rescue party equipped with the geophones and (2) for the procedure of a rescue party searching for entombed miners within the mine or from the surface.

PROCEDURE OF THE MINER.

A miner must always remember that energy used in breaking down coal is lost as sound energy; for that reason a tool with a fairly large striking surface should be used to strike the coal if the best results

are to be obtained by the man who is trying to make known his whereabouts. A sledge, a heavy stick of timber, or even a rock, make the best implements with which to pound. If a pick should be used, the blow should be struck with the head or the side of the pick, or a great deal of the miner's effort would be wasted in breaking the coal. The blow should be struck as heavily as possible without crushing the coal.

Furthermore, it is of course necessary that a solid place be chosen upon which to pound. This requirement really is the chief reason for the recommendation that all pounding be done on the coal, for the coal is usually more solid than the roof and the floor. Observation has disclosed a marked similarity between the sounds transmitted through the coal as heard through the geophone and those heard by the man striking the blows. For this reason the man striking the blows should be able to judge correctly the efficiency of his labors. These simple principles hold whether the miner expects the rescue party to be operating from the surface or from within the mine.

It is well known that a properly suspended pipe line will transmit the sounds from blows for great distances. It has been found, however, that the pipe will transmit such sounds only when properly suspended, and the sound transmission may be completely stopped if the pipe is covered with a small amount of loose dirt for a distance of 10 to 15 feet. Practically all pipe lines running along the floors of coal-mine entries are more or less covered with road dust, which renders them useless for sound transmission. For that reason if he expects his pounding to be detected by the geophone, and unless he knows that he has over 1,500 to 2,000 feet of unobstructed pipe line, a miner should not pound upon the pipe, for it is much more certain that his blows would be detected through the coal. What has been said regarding pipe lines applies also to rails in mine entries.

An entombed miner may be imprisoned for hours or even days before rescue parties can reach his section of the mine. Although it is desirable that the miner keep up a continuous pounding it is by no means necessary that this pounding be rapid. He should strike a number of quick successive blows, pause awhile, and repeat the signal. In the experimental work it was found that strokes of three—three blows, pause, three blows, pause, etc.—were very satisfactory for signaling, as such a signal is easily detected and unlikely to be produced accidentally in a mine. The signal should be repeated at least once every minute and oftener whenever possible. It is desirable to repeat the signal thus often, as an observer with the geophones should not feel obliged to listen longer than two or three minutes at one point unless he hears some signal. Also, he will need to listen to a number of signals before he gets a definite determination of the direction of the sound.

The miner should always be alert for signals from the rescue party. When a party approaching from within the mine comes within range they may signal by pounding, or possibly with explosive, although the occasions would be rare when explosive could be safely used. It has been found, however, that the explosion of a three-stick charge of 40 per cent nitroglycerin dynamite, fired upon the surface, can be heard within the mine if the cover is as much as 400 to 500 feet thick. Signals of threes should indicate to the entombed miner that the rescue party is in his neighborhood, and that he should redouble his efforts to be heard. If after these signals he hears signals of fives this will indicate to him that his pounding has been detected, and that the rescue party are satisfied that they have his location. On receiving signals of threes at any time, however, he should reply as best he can.

PROCEDURE OF THE RESCUE PARTY WITHIN THE MINE.

The problem of the member of a rescue party who has the geophones is first one of detection and then one of location. It has already been stated that the geophones should be placed on the coal, because the solid coal carries the sound waves better and transmits them more easily to the geophone. It has been ascertained, also, that if the geophones be held to the coal face or rib with the hands there is vibration enough from the blood circulating in the hands to cause a distinct roar within the instrument. The instruments therefore must be placed upon some horizontal surface—a projecting ledge or a niche cut into the coal. In some of the mines it is the custom to cut niches into the entry ribs in which to keep the explosives. Such niches form an ideal place to operate the geophones. If the operator can find no natural shelves or niches, he should cut some with a pick; for detection work it is necessary to make them just large enough to hold the instrument. As sounds are transmitted so well through the coal, it does not seem necessary that observation points be selected nearer together than from 500 to 700 feet. It probably will not be desirable for a man to remain at one point more than a few minutes, for if the entombed miner is following instructions he will strike often enough for the observer to hear him within a short space of time if he is to hear him at all.

Once the pounding is detected, the problem then becomes one of determining the direction of the source of the sound. Here the operator will be governed by conditions. If his niche or shelf is from 10 to 18 inches square, he will have plenty of room to manipulate his instruments in the usual manner, and will find that he can get accurate measurements in this way. If not, he may either make a larger niche with his pick or he may place his instrument upon the

floor. If the sound is intense enough to be detected with the instruments on the floor, he can determine the direction very accurately from there. He must be careful to avoid placing his instrument over ties, pipes, rails, etc., which might mislead him. If he can not hear the sound from the floor and does not care to dig a niche, it is reasonable to suppose that his map will indicate to him the point from which the miner is probably pounding. He may try to get closer to the sound, and on finding that he can hear the sound from the floor he may check up the direction and proceed toward the miner. In general his procedure will depend on conditions, but he must bear in mind the fact that sounds are most easily detected through the coal when the geophones are placed on the coal.

PROCEDURE OF THE RESCUE PARTY FROM THE SURFACE.

The possibility of locating an entombed miner from the surface depends not only on the thickness and the nature of the strata above the mine, but also to a large extent on the weather. It is evident that it would be impossible to use such a sensitive instrument as the geophone in a rainstorm, of if there were much wind. The wind would not interfere greatly by blowing across the tubes leading from the head to the instrument, but the noise produced by the motion in the grass and trees near by would be the disturbing factor. Experiments have shown that if the cover of a mine were not greater than 500 feet it would be possible under favorable conditions to hear pounding from within the mine. If a map showing the location of the mine with regard to the surface is available, a great deal might be accomplished with the geophone before it would be possible for the rescue party to enter the mine. By taking the instruments immediately to points above the working places considerable information might be obtained. In covering the surface it seems best that observations should be made at points from 300 to 350 feet apart.

Reference has also been made to the possibility of signaling from the surface to the miner by means of explosive. Whenever possible signaling by explosives should be attempted.

It should also be borne in mind that the geophone offers an excellent means of communication between the surface and a rescue party within the mine. If a person over the mine had a set of the instruments, it should be possible for him under favorable conditions to follow the rescue party if they cared to signal to him frequently by means of a set of prearranged signals. Also it would be possible to signal to the rescue party to withdraw immediately from the mine in case of danger, or for the rescue party to signal to the outside for help in case one of their party were overcome. Communication would probably always be better from the surface to the mine than from the mine to the surface.

If a party on the surface should attempt to follow the rescue party, they would adopt one of two possible methods of procedure. The men on the surface could attempt to follow frequent poundings of the interior party, or, if the probable course of the men in the mine were known, the surface party could establish itself at prearranged successive points above this route, and await signals that the interior party has arrived at these places. Experiment has shown that a sledge blow struck upon a piece of heavy iron or wood upon the surface usually can be heard farther through the cover than ordinary sledge pounding can be heard from the mine to the surface.

The geophones when employed on the surface should be placed in areas from which the sod has been carefully removed without disturbing the ground underneath.

PROCEDURE OF THE RESCUE PARTY IN METAL MINES.

Occasion might arise in a metal mine when the geophone would be valuable for rescue purposes. The great difference between most metal mines and coal mines is that the floor, roof, and ribs of an entry of a metal mine are frequently of the same material. This condition means that the geophones can be used on the floor unless there is too much muck. Furthermore, the rock seems to be firm enough to prevent the setting up of interfering vibrations when the geophones are held against it by the hands. Satisfactory results can be obtained therefore by holding the geophones firmly against the rock in any position. It will be noticed also that the clear transmission of the sound waves through the rock permits of ready determination of the direction of the sound.

USE OF GEOPHONE IN MINE SURVEYING.

Geophones supply a quick and fairly accurate method of mine surveying. They can be used to advantage, therefore, in guiding tunnels together, in preventing accidents at blasting through, and in locating mine fires, bore holes, faults, and "clay veins."

LOCATION OF TUNNEL HEADING.

If two tunnels were being brought together from any direction—the term tunnels here including drifts, slopes, and raises—the progress of the tunnels could be observed by means of the geophones, and their relative positions determined. Under ordinary circumstances surveys would be made in the usual way, yet the geophone offers a simple method of check on such surveys.

In following the course of two tunnels it would be best perhaps to pound in the center of the tunnel heading, in order to give a definite point upon which to make the determination of direction. The

observer in the other tunnel would use the geophones in the usual way. After observations were completed, the geophones should be taken into the other tunnel and check tests made.

It is unlikely that the observer would make a mistake regarding the apparent direction of the pounding unless the strata through which the sound was coming were unhomogeneous. If the strata deflect the sound from its true course, it would usually become apparent in making the check observations, as it is improbable that the sound would take the same irregular course in both directions.

The practical value of the geophone in this connection can be seen from the following example. The Bureau of Mines engineers were fortunate in being present in a metal mine at the time when a drift and a raise had "missed." A few minutes of observation in the drift, and of pounding in the raise, showed that the raise had gone up past the drift about 6 feet in from the face and to the right. Observations made from the raise to the sounds of the drill operating in the drift showed that the raise extended to a point 6 feet above the drift, and that the drift was in the direction indicated by the first set of observations. A survey showed these conclusions to be correct. Again, observations were made of another raise that was being driven up by a drift about 6 to 8 feet back. Observations were made of the sounds from the drill, and a point was located on the side of the drift behind which the drill in the raise seemed to be working. The survey mark was then ascertained to be from 2 to 3 feet to the right of this mark. A drill set up at the survey mark did not hole through into the raise. A hole drilled at the point indicated by the geophones reached the raise, and proved the geophone observations to be correct within a few inches.

"Clay veins," as has already been pointed out, are the greatest hindrance to the transmission of sound because their density is so different from that of neighboring strata.

PREVENTION OF ACCIDENTS IN BLASTING THROUGH.

Another application of the possibilities of the instrument in surveying is in the prevention of accidents in blasting through. If two tunnels are approaching each other, or are passing a short distance apart, it is necessary to determine the relative location in order that men may be warned to keep away from the point of danger. As the sounds transmitted through the geophone are so characteristic, frequent observation would enable a trained observer to follow the progress of the work in the opposite tunnel. He would thus be able to tell when blasts were to be fired.

LOCATION OF MINE FIRES.

Usually a mine fire makes enough noise, either by drawing air or by breaking off slate and coal, to be heard for a considerable distance

through the coal and even through the strata above. The distance that these sounds can be heard depends a great deal on the nature of the strata above the mine, yet the sounds originating at a mine fire should be detected through 100 to 300 feet of cover and through 500 to 800 feet of coal. During observations made above one mine fire that was burning about 40 feet below the surface, occasional sounds were heard as if air were being drawn through crevices. There was

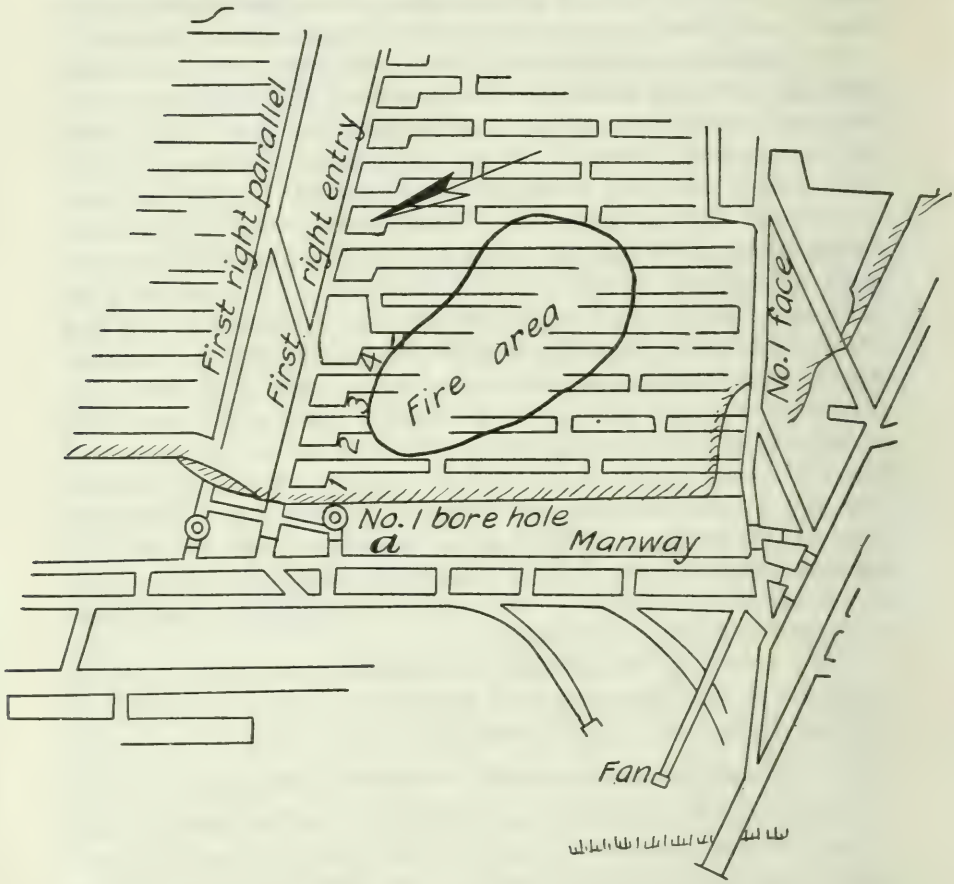


FIGURE 12.—Location of the area of a mine fire by the geophone.

also a more or less continuous series of sounds such as would be made by the dropping off and falling of small pieces of roof. The area of the fire was determined from the surface, as shown by figure 12. The only point within the mine where similar sounds could be detected was the point *a*. It is easily seen that this point is the nearest one accessible to the fire area, as located from the surface.

A few months later observations were made around the base of a large burning culm pile. It was significant to note that exactly the same types of sounds were audible there.

As compared with the above, it may be added that at another fire in the anthracite region no sounds were audible either on the surface or within the mine, even when the fire was approached so closely that both the ground and coal were warm to the touch. This fire was, however, quiescent.

At a third fire, also in the anthracite region, in workings near the surface, sounds were distinctly audible and observations showed that those noises could be detected through 100 feet of ground.

To summarize, when mine fires are merely in a smouldering stage, the geophone is not of any help, but when the fire is raging in open workings, not accessible from one cause or another, and the distance to the surface is not much over 100 feet, the geophone may be of value in determining the fire area, and thus enable measures to be taken for extinguishment or limitation.

LOCATION OF CHURN-DRILL HOLES.

Occasionally churn-drill holes are dropped from the surface to mine workings for running pipes and for ventilation. When these borings come for considerable distances they sometimes drift, and instead of breaking through into the workings, they come down into the solid. The question then is to locate them and to determine whether or not the hole is deep enough to come into the workings. Here the geophone finds a useful field, for not only the direction of the hole, but its elevation can be determined accurately. The best procedure would be to listen to the drill working in the hole as the hole approaches the level of the workings.

LOCATION OF THE DRIFT OF DIAMOND-DRILL HOLES.

It is well known that when the bit of a diamond drill has disappeared below the surface there is no simple method for determining the course it may have taken. As these bits nearly always drift away from a straight course, any instrument making it possible to follow this drift will obviously be valuable. The geophones should be useful for this purpose. At the time of writing this phase of the investigation of geophones in surveying had not been completed. Observations have been made upon only two vertical drill holes, which apparently had not deviated from their course. These holes, situated about a quarter of a mile apart, were penetrating rock strata consisting of alternate layers of gneiss and black rock. The rock seams pitched at an angle of about 45°. One hole had reached a depth of approximately 1,000 feet, the other 600 feet. At each hole it was possible to hear the bits cutting when the geophones were placed upon the rock surface. The observations were somewhat disappointing in that the sounds of the bits could be heard within a limited area only, a circle

whose radius was approximately 100 feet, the drilling machinery being located within the center of this area. As the area was so small, and supposedly directly above the bit, no determinations of directions could be made in the usual manner. It is believed, however, that had the bits drifted, this area of audibility would have been directly above the bit and away from the drilling machinery. Observations will have to be made of angle holes in order to prove this point. It is certain that should a drill hole be put down ahead of mine workings there would be no difficulty in locating the drill hole from the workings themselves.

LOCATION OF "FAULTS" AND "CLAY VEINS."

Reference has been made to the fact that sound is transmitted but poorly through or across "faults" and "clay veins." It is occasion-

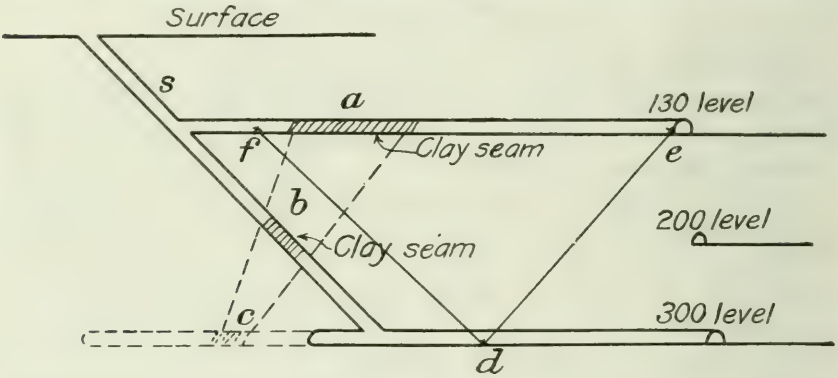


FIGURE 13.—Vertical section of a metal mine in which a clay vein was located by geophones.

ally useful to determine the existence of such veins, and here the geophones will be of value. One case has come to the attention of the author and is herewith described. In figure 13 is represented the vertical section of part of a certain metal mine. The tunnel on the 130-foot level crosses through a loosely organized clay seam at *a*. The slope *s* also crosses a seam at *b* which is presumably the same seam as *a*, and if the tunnel on the 300-foot level is prolonged to a point about *c* this same clay vein probably will be encountered. If the clay seam is continuous from *a* to *b* there should be little sound transmitted in this position. Point *d* was selected on the lower level as being equally distant from two points *f* and *e* on the upper level, the one point *f* being located on the other side of the supposed continuous vein, point *e* on the same side of the vein as *d*. It was determined that pounding at point *d* could not be heard at *f* though such pounding was distinctly audible at *e*. The conclusions were

that the clay seam was a continuous one and that it would probably be encountered on the 300 level.

OTHER USES OF THE GEOPHONE.

LOCATION OF LEAKS IN WATER PIPES.

By means of the geophones it is possible to hear water circulating in the pipes of the ordinary city mains situated 10 to 15 feet below the surface. The instrument is of value therefore to locate the position of pipe lines and should also be useful to locate leaks. That it can be so employed is demonstrated by the following test carried out at one of the busy corners of the Pittsburgh business district.

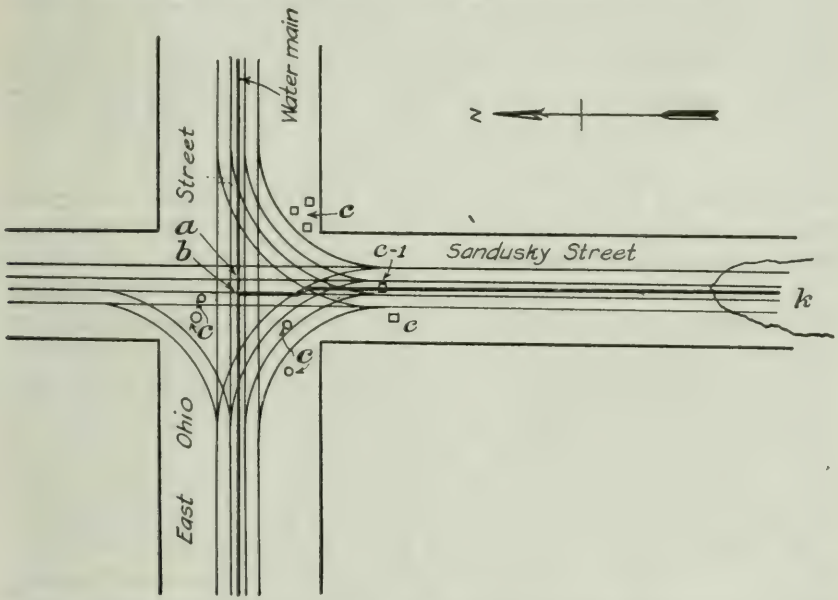


FIGURE 14.—Diagram of intersection of two Pittsburgh streets, showing leak in water main located by geophones.

Figure 14 illustrates this test. Water was found to be seeping through the joints of the paving blocks at the point *k*. This area was approximately 150 feet from the intersection of two streets. When the geophones were placed upon the paving at this point the sound of running water could be heard, the water seeming to come from the north. Sandusky Street at this point has a slight grade sloping to the south. At the time the observations were made the water company had been watching the leak for about two weeks and could obtain no information indicating the location of the trouble.

All the information it had was that the water was seeping out through the paving at k and that all of the gate boxes on the south side of East Ohio Street were full of water. Sounds of running water were first heard at k, and were followed back to gate box c_1, where the sounds were very loud. It was thought at first that the leak was located at c_1. Upon moving toward the center of the intersection of the street, however, the sound of running water was supplemented by a hissing sound. This sound could be heard anywhere within a radius of 40 feet, and determinations of direction all showed that it came from the supposed location of a T where the 10-inch main running down Sandusky Street joined the 15-inch main on East Ohio Street. The water company's map showed that the T was located at the exact center of the intersection of the streets. The geophones showed so conclusively that the leak was in the T that accurate observations were not made to locate the sounds with respect to the center line of the street. Digging showed that the T was 3 feet west of the point shown in the company's map. The water was issuing from one of the joints of this T. The leak had been located by means of the geophones with enough accuracy that only one hole was put down from the surface. The slight error was due to failure to check the map by careful determinations of direction.

In a second test the results were not so satisfactory. An account of these observations is given to show the care necessary to prevent the observer from being misled. There was a leak in a 1-inch pipe leading from a street main to a residence. The sound from the leak was transmitted along the pipe to the house and could be heard by placing the ear to the pipe in the cellar of the house. The pipe was buried about 10 feet below the surface. Observations made upon the cellar floor pointed to the fact that the leak was probably close to the cellar wall near the point at which the pipe entered the cellar. Similar results were obtained from the surface. The sounds coming from the leak were distinctly audible close to the cellar wall, and as they were not heard elsewhere in the yard there was little doubt that the leak was at this point. As the continuous passing of heavy trucks interfered with the work, however, observations were made later during the evening quiet. This time the sounds from the leak could be heard faintly on the surface at points from 15 to 20 feet from the house. The leak was later found to be here. Plate II (see p. 11) shows a section of this pipe and the split from which the water was issuing. The geophone operators were at first misled by the sound of the leak traveling along the pipe until the pipe came in contact with the solid masonry of the house foundation, when the sound was transmitted through the masonry.

EARTH MOVEMENTS.

No attempt has been made to adapt the geophone to determine the earth movements that sometimes occur in deep mines and are termed "bumps" by the miners, but it is believed the instrument will prove adaptable, although in its present form its use for this purpose would require a person to "listen" at such times as observations are taken. The difficulty in using it for this purpose would be to distinguish ordinary sounds produced by blasting and other mining operations from the sounds caused by ground movement. When no work is being done in the mine by men or machinery the strata movement could be determined and a warning could be given to prevent workmen from entering the part of the mine from which the sounds came.

It is probable that this instrument may be of some use in certain parts of the anthracite coal field where cave-ins have destroyed mine workings, causing loss of life, surface subsidence, and injury and destruction of buildings.

MATERIAL FOR GEOPHONE DIAPHRAGMS.

An investigation to determine the most suitable material for geophone diaphragms showed that in mica diaphragms the thickness was not an important factor. Metal diaphragms were not only more satisfactory than the mica, but their sensitiveness increased with thickness until a point was reached when a ringing tone was produced and the diaphragms therefore became useless. With the exception of Non Gran bearing metal, a material 0.025 inch thick was the maximum thickness that could be used. With Non Gran bearing metal, however, a diaphragm 0.035 inch thick was satisfactory.

To determine the sensitiveness of the diaphragms, observations with the geophones were made on blows struck with a $5\frac{3}{4}$-pound hammer swung as a pendulum against the coal at a distance of 400 feet away from the observer. The swing of the pendulum was measured, and the shortest swing that could be detected with the geophones was recorded. The results obtained at the experimental mine with the different materials follow:

TABLE 3.—*Sensitiveness of diaphragms of geophones made of different metals tested in the experimental mine.*

Material.[a]	Thickness.	Energy.	Distance.
	Inch.	*Foot-pounds.*	*Feet.*
Mica	0.015	0.3196	400
Do	.025	0.3196	400
Phosphor bronze	.007	.3196	400
Do	.015	.1797	400
Do	.025	.07986	400
Non Gran bearing metal	.025	.01996	400
Do	.035	.004989	400
Pure nickel	.025	.004989	400
Full-spring nickel-silver	.025	.01996	400
Half-spring nickel-silver	.025	[b] .004989	400
Pure aluminum	.025	.07986	400
Aluminum alloy	.025	.01996	400
Duralumin	.025	.01996	400
Untempered steel	.025	.01991	400
Untempered chrome-vanadium steel	.025	.01991	400
Solvay steel	.025	.01991	400
Festal metal	.025	.3196	400

[a] Various brasses were investigated, but in every test the material at hand was found to be too thick to give suitable results.

[b] The sound was much fainter than that obtained with the use of the Non Gran or nickel diaphragm.

PUBLICATIONS ON MINE RESCUE OPERATIONS.

A limited supply of the following publications of the Bureau of Mines has been printed and is available for free distribution until the edition is exhausted. Requests for all publications can not be granted, and to insure equitable distribution applicants are requested to limit their selection to publications that may be of especial interest. Requests for publications should be addressed to the Director, Bureau of Mines.

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PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION.

TECHNICAL PAPER 11. The use of mice and birds for detecting carbon monoxide after mine fires and explosions, by G. A. Burrell. 1912. 15 pp.

TECHNICAL PAPER 82. Oxygen mine rescue apparatus and physiological effects on users, by Yandell Henderson and J. W. Paul. 1917. 102 pp., 5 pls., 6 figs.

TECHNICAL PAPER 103. Organizing and conducting safety work in mines, by H. M. Wilson and J. R. Fleming. 1917. 54 pp., 35 figs.

MINERS' CIRCULAR 4. The use and care of mine rescue breathing-apparatus, by J. W. Paul. 1911. 24 pp., 5 figs.

MINERS' CIRCULAR 10. Mine fires and how to fight them, by J. W. Paul. 1912. 14 pp.

Rescue and recovery operations in mines after fires and explosions, by J. W. Paul and H. M. Wolflin. 1916. 109 pp.

PUBLICATIONS THAT MAY BE OBTAINED ONLY THROUGH THE SUPERINTENDENT OF DOCUMENTS.

BULLETIN 44. First national mine-safety demonstration, Pittsburgh, Pa., October 30 and 31, by H. M. Wilson and A. H. Fay, with a chapter on the explosion at the experiment mine, by G. S. Rice. 1912. 75 pp., 7 pls., 4 figs. 15 cents.

BULLETIN 62. National mine rescue and first aid conference, Pittsburgh, Pa., September 23–26, 1912, by H. M. Wilson. 1913. 74 pp. 10 cents.

TECHNICAL PAPER 77. Report of the committee on resuscitation from mine gases, by W. B. Cannon, G. W. Crile, Joseph Erlanger, Yandell Henderson, and S. J. Meltzer. 1914. 35 pp., 4 figs. 5 cents.

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